

THE EFFECT OF LOADING ON KINEMATIC AND KINETIC VARIABLES DURING THE MIDTHIGH CLEAN PULL

PAUL COMFORT, REBECCA UDALL, AND PAUL A. JONES

Directorate of Sport, Exercise, and Physiotherapy, University of Salford, Salford, Greater Manchester, United Kingdom

ABSTRACT

Comfort, P, Udall, R, and Jones, PA. The effect of loading on kinematic and kinetic variables during the midthigh clean pull. *J Strength Cond Res* 26(5): 1208–1214, 2012—The ability to develop high levels of muscular power is considered a fundamental component for many different sporting activities; however, the load that elicits peak power still remains controversial. The primary aim of this study was to determine at which load peak power output occurs during the midthigh clean pull. Sixteen participants (age 21.5 ± 2.4 years; height 173.86 ± 7.98 cm; body mass 70.85 ± 11.67 kg) performed midthigh clean pulls at intensities of 40, 60, 80, 100, 120, and 140% of 1 repetition maximum (1RM) power clean in a randomized and balanced order using a force plate and linear position transducer to assess velocity, displacement, peak power, peak force (F_z), impulse, and rate of force development (RFD). Significantly greater F_z occurred at a load of 140% ($2,778.65 \pm 151.58$ N, $p < 0.001$), impulse within 100, 200, and 300 milliseconds at a load of 140% 1RM (196.85 ± 76.56 , 415.75 ± 157.56 , and 647.86 ± 252.43 N·s, $p < 0.023$, respectively), RFD at a load of 120% ($26,224.23 \pm 2,461.61$ N·s⁻¹, $p = 0.004$), whereas peak velocity (1.693 ± 0.042 m·s⁻¹, $p < 0.001$) and peak power ($3,712.82 \pm 254.38$ W, $p < 0.001$) occurred at 40% 1RM. Greatest total impulse ($1,129.86 \pm 534.86$ N·s) was achieved at 140% 1RM, which was significantly greater ($p < 0.03$) than at all loads except the 120% 1RM condition. Results indicate that increased loading results in significant ($p < 0.001$) decreases in peak power and peak velocity during the midthigh clean pull. Moreover, if maximizing force production is the goal, then training at a higher load may be advantageous, with peak F_z occurring at 140% 1RM.

KEY WORDS peak power, peak force, rate of force development

Address correspondence to Paul Comfort, p.comfort@salford.ac.uk.
26(5)/1208–1214

Journal of Strength and Conditioning Research
© 2012 National Strength and Conditioning Association

INTRODUCTION

The ability to develop high levels of muscular power is considered a fundamental component for many different sporting activities; particularly in sports that require explosive production of force such as jumping, throwing, changes of direction, and acceleration (3). For these activities, power output is considered the foremost determinant of performance (21,22). Power is a product of force and velocity, which have an inverse relationship; thus, it is imperative to train both of these variables effectively. Force and velocity are linked variables, as the velocity of a movement increases, the ability to generate concentric force decreases (21,22).

It has been suggested that when training to increase muscular power using loads which emphasizes the athlete's maximum power output may be advantageous for maximizing improvements in performance (3,8,23,24). Previous research has stated that training at the optimal load is most effective in improving maximal power output (5–7,20,25,35). However, there appears to be a spectrum of loads at which peak power is achieved across different exercises (17); it is suggested that peak power output, during the squat jump lies at 0% of 1 repetition maximum (1RM) back squat (3,5,6), although Stone et al. (29) found that peak power occurred at 10% of 1RM in weaker athletes and 40% 1RM in strong athletes; however, they did not assess <10% 1RM. Similarly, Thomas et al. (31) found peak power output during the squat jump to be elicited between 30 and 40% 1RM in men and 30–50% 1RM in women. In contrast, peak power output during variations of the clean have been shown to occur at loads between 70 and 80% 1RM power clean (6,21–23).

It has been suggested that Olympic style lifts increase an athlete's performance by imitating sport-specific movements, while concurrently using explosive power (28–30), with performance in the hang power clean being correlated to both 20-m sprint and countermovement jump performance (19). In light of this, research has investigated optimal loading for variations of the clean (5,6,18,23). One study into hang power cleans found peak power to lie at 70% (21), although Cormie et al. (5) identified 80% as the load that elicited peak power. Kilduff et al. (23) also researched peak power output during hang power clean; however, they reported no

significant differences were found between loads of 50, 60, 70, 80, and 90% 1RM, although the peak power did occur at 80% 1RM.

In contrast to the other variations of the clean, Kawamori et al. (22) found that peak power during the midhigh clean pull peaked at 60% 1RM, with Thomas et al. (31) identifying peak power during hang-clean pulls to occur between 30 and 60% 1RM. The midhigh clean pull is the second pull of the clean; it is the most explosive element of the movement and generates the greatest force and power compared with the other phases of the lift (10–14,16,26,27). Enoka (10) studied experienced weightlifters' technique during the pull phase of a clean, finding that subjects created a peak ground reaction force (GRF, F_z) of 2,471 N during the first pull phase, whereas the second pull phase created a greater peak F_z with an average of 2,809 N. Häkkinen et al. (16) found similar results, with the second pull displaying the greatest peak F_z at 150% of the system load, with Garhammer (11–14) also identifying the second pull phase as eliciting the highest power output compared with the first pull across weight classes in Olympic weightlifters. More recently, Comfort et al. (4) found that peak F_z and rate of force development (RFD) was significantly greater ($p < 0.001$) during the midhigh power clean ($2,801.7 \pm 195.4$ N; $14,655.8 \pm 4,535.1$ N·s⁻¹) and the midhigh clean pull ($2,880.2 \pm 236.2$ N; $15,320.6 \pm 3,533.3$ N·s⁻¹) compared with both the power clean ($2,306.2 \pm 240.5$ N; $8,839.7 \pm 2,940.4$ N·s⁻¹) and the hang power clean ($2,442.9 \pm 293.2$ N; $9,768.9 \pm 4,012.4$ N·s⁻¹) at a load of 60% 1RM power clean. Rather surprisingly, no studies have previously reported the optimal load that peak impulse is achieved during various explosive lifts. The impulse achieved within a time period reminiscent of the ground contact phase of sprinting (≤ 200 milliseconds) (32–34) and jumping activities could be critical to performance based on the impulse change in momentum relationship. Thus, maximizing impulse during explosive lifts in training through the selection of appropriate loads would be highly desirable.

The optimal load required to elicit peak power during different exercises still remains controversial with inconsistencies within the literature as to the intensity resulting in peak power. Only Kawamori et al. (22) has previously attempted to determine the load that optimizes peak power output during the midhigh clean pull, identifying that peak power is achieved at 60% of 1RM (power clean) when comparing loads of 30, 60, 90, 120% of 1RM, in collegiate weightlifters. Kinetic and kinematic performances of such exercises may vary between weightlifters and team sport athletes because of technical proficiency. Therefore, the aim of this study was to investigate the effect of loading (40, 60, 80, 100, 120, 140% 1RM power clean) on kinematic (peak bar velocity, bar displacement) and kinetic variables (peak power, peak F_z , peak RFD, and impulse) in team sport athletes, to identify the optimal load to train explosive force production and power. It was hypothesized that bar displacement,

velocity, and therefore peak power would be greatest at the lower loads and decrease as load increased, whereas F_z , RFD, and impulse would increase with increased load and peak at 140% 1RM.

METHODS

Experimental Approach to the Problem

This study employed a within subject's repeated-measures research design; whereby kinematic (displacement, velocity) and kinetic (peak F_z , peak power, RFD, and impulse) variables were determined during the midhigh clean pull. The abovementioned variables were measured by the subject performing all lifts on a Fitness Technology 700 ballistic measurement system with integrated force plate and linear transducer sampling at 600 Hz (Fitness Technology, Adelaide, Australia) using loads of 40, 60, 80, 100, 120, 140% 1RM power clean, to determine differences in kinematic and kinetic variables between loads.

Subjects

Sixteen healthy collegiate athletes (age 21.5 ± 2.4 years; height 173.86 ± 7.98 cm; body mass 70.85 ± 11.67 kg), who participate in team sports, were recruited on the basis that they had been engaged in a structured weight training program for at least 2 years before the start of the study and were also able to perform the power clean with correct technique as assessed by a certified strength and conditioning coach. The average training experience of the group was 3.51 ± 0.86 years, and all testing was conducted in season. The study was approved by the institution's Ethics Committee, and all the subjects provided informed consent before participation.

One-Repetition Maximum Testing

Before commencement of the main experimental trial, the subjects visited the laboratory on 2 occasions to establish the reliability of the 1RM power clean, following the protocol of Baechle et al. (1). In addition, after the 1RM assessments, the subjects were familiarized with the midhigh clean pull protocol. A certified strength and conditioning coach was present at each session to assess the quality of each lift. All testing was performed using a lifting platform (Power Lift, Jefferson, IA, USA), Olympic bar and Olympic weights (Werksan, NJ, USA). The greatest load achieved across the 2 sessions was used to calculate the relative load for the power testing.

Power Testing

The subjects reported to the laboratory on the morning of testing having refrained from caffeine, alcohol, and strenuous exercise for 48 hours. Each completed a standardized warm-up, low-intensity cycling ($\sim 60\%$ maximum heart rate) for 5 minutes, followed by 1 set of 3 repetitions of the midhigh clean pulls at 40% 1RM power clean. The subjects were then required to complete midhigh clean pulls at intensities of 40, 60, 80, 100, 120, and 140% of their predetermined 1RM in a randomized and balanced order. All the lifts were

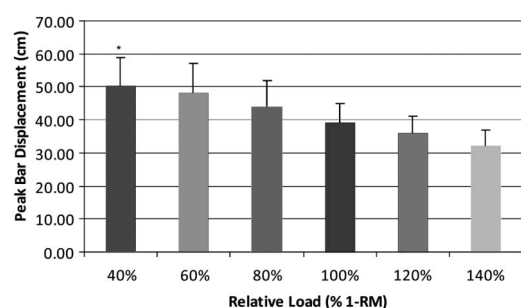


Figure 1. Comparison of displacement across loads.

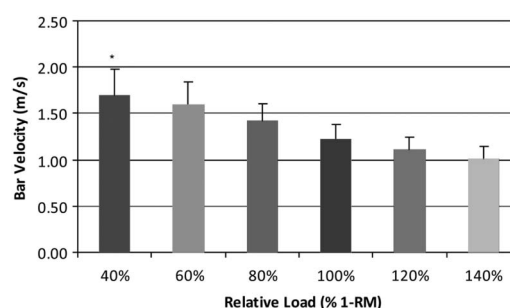


Figure 2. Comparison of peak bar velocity across loads.

performed on the Fitness Technology 700 ballistic measurement system with integrated force plate and linear position transducer (LPT) sampling at 600 Hz, interfaced with a laptop and ballistic measurement software. Three repetitions were performed at each load with 30 seconds of rest between repetitions and 4 minutes between loads to minimize fatigue. Verbal encouragement was provided throughout testing. The subjects lowered the bar to midthigh, paused and then performed the exercise, ensuring a triple extension of the ankle, knee, and hip and an upwards shrug that moved the bar in a vertical plane while maintaining elbow extension. Any repetitions that initiated with a countermovement were disallowed and repeated after a further a 30-second rest period.

Barbell velocity and displacement were determined via the LPT. Displacement-time data was smoothed using a Butterworth fourth-order digital low-pass filter with a cut-off frequency of 16 Hz before differentiation using finite difference technique. Barbell velocity was obtained via differentiation of the displacement-time data of the barbell.

To determine power, velocity of the center of gravity (COG) of the system (barbell \pm body) was calculated from vertical GRF time data based on the relationship between impulse and momentum in which impulse is equal to the changes in momentum (forward dynamics approach). Power applied to the system was calculated as the product of velocity of the COG of the system and F_z at each time point (5,6,18). The RFD was determined by dividing the difference in consecutive vertical force readings by the time interval (0.0017 seconds) between readings (4,22). Impulse at 100, 200, 300 milliseconds and total impulse were also calculated. The time intervals were selected based on typical ground contact phases for the various sprint, jump, and change of direction activities that would be experienced by the team sport athletes used in the present study (32–34).

Statistical Analyses

Intraclass correlation coefficients (ICCs) were performed to determine the reliability of 1RM performances and to determine the repeatability of performances between repetitions

for each dependent variable, using the criteria of Cortina (9), where $r \geq 0.80$ is highly reliable. A repeated-measures ANOVA, with Bonferroni post hoc analysis was conducted using SPSS (version 17.0) to determine if there were any significant differences in each dependent variable within subjects between lifts and loads. An apriori alpha level was set to $p \leq 0.05$.

RESULTS

The ICCs revealed a high reliability between 1RM power cleans ($r = 0.96$, $p < 0.001$). The ICCs for each variable demonstrated high reliability for velocity ($r = 0.935$, $p < 0.001$), displacement ($r = 0.954$, $p < 0.001$), peak power ($r = 0.981$, $p < 0.001$), F_z ($r = 0.995$, $p < 0.001$), and impulse ($r = 0.810$, $p < 0.001$), at each intensity; RFD, however, showed only a moderate reliability ($r = 0.619$, $p = 0.012$).

Sphericity could not be assumed via Mauchleys' test ($p < 0.05$), and therefore, sphericity was assumed by means of the Greenhouse-Geisser adjustment ($p < 0.001$). Observed power for all dependent variables was ≥ 0.98 .

Bar displacement showed a progressive decrease as load increased. Repeated-measures ANOVA demonstrated a significant ($p < 0.001$) difference for displacement across loads, with Bonferroni post hoc analysis revealing significantly greater ($p \leq 0.02$) bar displacement at the 40% load compared with all other loads. Peak bar displacement was significantly ($p \leq 0.02$) different across all loads (Figure 1).

Velocity showed a linear decrease as load increased. The repeated-measures ANOVA demonstrated a significant ($p < 0.001$) difference for velocity across loads, with Bonferroni post hoc analysis revealing significantly greater ($p < 0.001$) bar velocity ($1.69 \pm 0.042 \text{ m}\cdot\text{s}^{-1}$) was achieved during the 40% condition, compared with all other loads (Figure 2). Bar velocity was significantly ($p < 0.001$) different across all the loads.

Peak F_z showed a progressive increase as load increased, although this was not statistically significant ($p > 0.05$) between 60% ($2,573.65 \pm 141.26 \text{ N}$), 80% ($2,581.75 \pm 140.68 \text{ N}$), and 100% ($2,591.37 \pm 140.39 \text{ N}$). Significantly greater ($p \leq 0.02$)

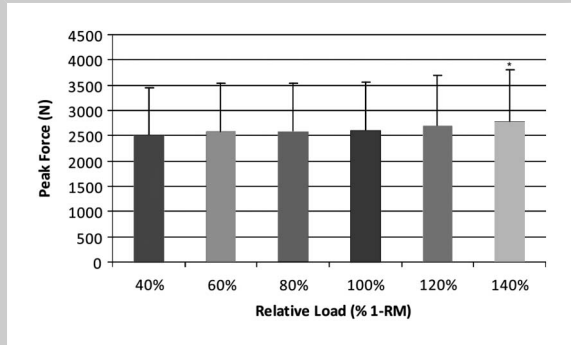


Figure 3. Comparison of peak force across loads.

peak F_z ($2,778.65 \pm 151.58$ N) was achieved during the 140% condition, compared with 120% ($2,680.95 \pm 149.10$ N), 100% ($2,591.37 \pm 140.39$ N), 80% ($2,581.75 \pm 140.68$ N), 60% ($2,573.65 \pm 141.26$ N), and 40% ($2,511.65 \pm 136.87$ N) (Figure 3).

Peak power decreased significantly ($p < 0.001$) as load increased. Significantly greater peak power ($3,712.82 \pm 254.38$ W) was achieved during the 40% condition, compared with the 80%, ($3,239.39 \pm 210.92$ W), 100% ($2,843.08 \pm 172.18$ W), 120% ($2,736.08 \pm 181.36$ W), and 140% ($2,542.49 \pm 155.08$ W) loading conditions, although this was not significantly ($p > 0.05$) greater than the 60% ($3,604.13 \pm 259.89$ W) condition (Figure 4).

Repeated-measures ANOVA demonstrated a significant ($p = 0.004$) difference for RFD across loads. Bonferroni post hoc analysis revealed the greatest RFD occurred at 120% ($26,224.23 \pm 2,461.61$ N·s⁻¹), which was significantly greater ($p \leq 0.004$) than the 40% ($17,308.36 \pm 1,256.34$ N·s⁻¹), 60% ($15,204.27 \pm 1,166.70$ N·s⁻¹), 80% ($17,063.02 \pm 2,214.52$ N·s⁻¹), and 100% ($19,400.79 \pm 2,087.92$ N·s⁻¹) loading conditions. However, this was not significantly ($p > 0.05$) greater than the 140% condition ($25,140.71 \pm 2,412.17$ N·s⁻¹) (Figure 5).

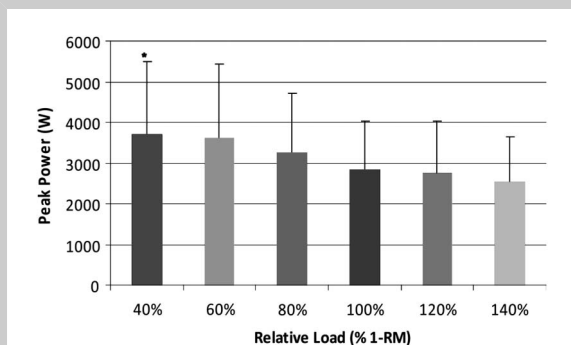


Figure 4. Comparison of peak power across loads.

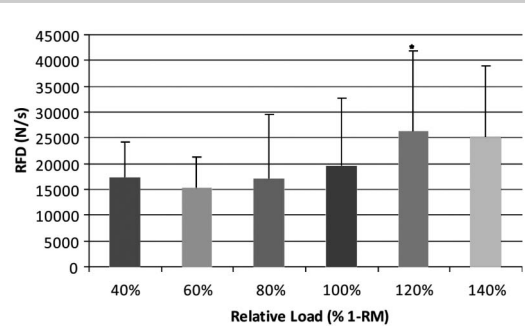


Figure 5. Comparison of rate of force development across loads.

Impulse at 100, 200, 300 milliseconds and total impulse showed an almost linear increase as load increased. Repeated-measures ANOVA demonstrated a significant ($p < 0.001$) difference for impulse at each time point (100, 200, 300 milliseconds and total impulse), across each load. The greatest impulse over 100 milliseconds (196.85 ± 76.56 N·s), 200 milliseconds (415.75 ± 157.56 N·s), 300 milliseconds (647.86 ± 252.43 N·s) was observed in the 140% 1RM condition, which was significantly ($p \leq 0.005$, $p \leq 0.023$, $p \leq 0.011$, respectively) greater than all other loading conditions. The highest total impulse ($1,129.86 \pm 534.86$ N·s) was observed in the 140% loading condition, which was significantly greater ($p \leq 0.03$) than the 40% (640.99 ± 321.28 N·s), 60% (736.69 ± 273.90 N·s), 80% (800.39 ± 301.35 N·s), and 100% (939.49 ± 411.53 N·s) conditions, but not significantly ($p > 0.05$) different to the 120% ($1,062.41 \pm 455.64$ N·s) condition (Figure 6; Table 1).

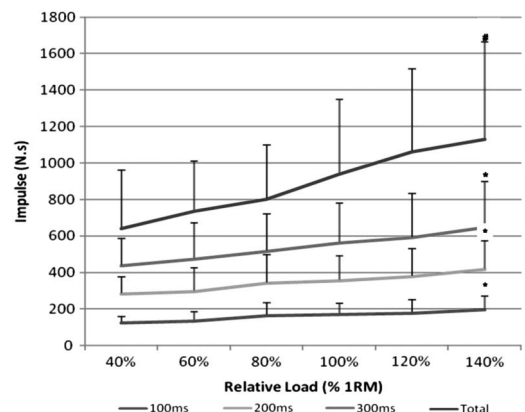


Figure 6. Affect of load on various measures of impulse.

TABLE 1. Affect of load on various measures of impulse.

Duration (ms)	Impulse	40%	60%	80%	100%	120%	140%
100	Mean (N-s)	125.20	132.85	163.37	170.26	178.45	196.85*
	SD	35.34	54.58	73.73	64.11	74.22	76.56
200	Mean (N-s)	283.36	295.53	342.61	355.33	378.07	415.75*
	SD	94.69	130.67	156.11	137.14	154.10	157.56
300	Mean (N-s)	437.19	471.53	515.20	559.97	591.40	647.86*
	SD	149.02	201.60	208.70	221.64	244.11	252.43
Total	Mean (N-s)	640.99	736.69	800.39	939.49	1062.41	1129.86†
	SD	321.28	273.90	301.35	411.53	455.64	534.86

*Significantly greater than all other loading conditions ($p < 0.023$).†Significantly >40, 60, 80, and 100% 1 repetition maximum ($p < 0.03$).

DISCUSSION

The aim of the study was to identify the changes in kinematic and kinetic variables across progressive loads. The combination of the alterations in force and velocity across loads resulted in peak power output occurring at a load of 40% 1RM ($3,712.82 \pm 254.38$ W), which was significantly ($p < 0.001$) greater than the power output achieved during the 80, 100, 120, and 140%; although not significantly ($p > 0.05$) different to the 60% ($3,604.13 \pm 259.89$ W) loading condition. These findings are in contrast to the previous findings of Kawamori et al. (22) who identified that peak power ($2,228.9 \pm 192.3$ W) was achieved at 60% of 1RM (power clean) when comparing loads of 30, 60, 90, 120% of 1RM, but in line with the findings of Thomas et al. (31) who found peak power (men $1,484.5 \pm 134.7$ W; women $1,384.4 \pm 111.9$ W) occurred between 30 and 60% 1RM. Peak power achieved at higher loads by Kawamori et al. (22) is likely a result of the subjects being experienced collegiate weightlifters who may demonstrate a higher level of competence in such exercises, whereas Thomas et al. (31) used collegiate soccer players, similar to our study. Differences in absolute power values may be a result of differing methods: Thomas et al. (31) used an inverse dynamics approach calculating barbell velocity via an LPT, Kawamori et al. (22) used a forward dynamics approach but subtracted body weight from the vertical GRF, whereas we used forward dynamics and included body weight as this is accelerated during the exercise.

Because power is a product of force and velocity, it is likely that peak power output in this study occurred at 40% 1RM because of a 69% decrease in velocity, compared with the 140% loading condition in contrast to only a 10.6% increase in F_z . In light of the fact that previous research suggests that training at the optimal load is most effective in improving maximal power output (5–7), these findings are important for program design.

Similar to the peak power findings, peak velocity was found to be significantly ($p < 0.001$) greater at a load of 40%

(1.69 ± 0.04 m·s⁻¹), compared with all other loading conditions, with a progressive decrease in velocity as load increased. Peak F_z , however, was identified at a load of 140% ($2,778.65 \pm 151.58$ N); as the load increased there was a slight, but linear increase in peak F_z .

Baker et al. (2) suggests that stronger individuals maximize power output at a different relative intensity than less strong individuals. Thus, this indicates that the optimal load may be subject to training and training status within the yearly periodized cycle. Furthermore, Stone et al. (29) reported that stronger subjects reached peak power during the jump squat at a higher relative load (40% 1RM) when compared with weaker subjects (10% 1RM), which may explain the differences in the findings of Kawamori et al. (21) with this study. Because of a low relative strength (0.93 ± 0.22 -kg·bw⁻¹ power clean) of athletes within this investigation it was not possible to make comparisons based on different strength levels.

It is likely that the higher loads (70–80% 1RM) previously identified to elicit peak power output during the power clean and hang power clean (5,15,21,23) are as a result of the additional phases of the clean (first pull and transition to midthigh, or transition to midthigh only) permitting greater time and range of motion to accelerate the bar before the second pull phase, technically unloading the bar because of its momentum. Conversely, it is interesting to note that the load that appears to elicit peak power output during this study is similar to the loads identified during the squat jump by Stone et al. (29), although greater than the loads (0% 1RM; body mass) by Cormie et al. (5,6). This may be attributable to the similar lower limb mechanics during the squat jump and midthigh clean pull, and it is recommended therefore that further research assess kinetic variables during the midthigh clean pull across a greater spectrum of loads.

Comfort et al. (4) researched RFD during variations of the clean; power clean, hang power clean, midthigh power clean, and midthigh clean pull, using 60% 1RM; results concluded

that midhigh clean pull and midhigh power clean demonstrated the highest instantaneous RFD when compared with the clean or power clean. Peak RFD of the midhigh clean pull was reported to be $15,320.2 \pm 3,533.3 \text{ N}\cdot\text{s}^{-1}$, which is similar to the RFD observed in this study when using 60% 1RM ($15,204.3 \pm 1,166.7 \text{ N}\cdot\text{s}^{-1}$); however, in this study, peak RFD at 120% 1RM ($26,224.2 \pm 2,461.6 \text{ N}\cdot\text{s}^{-1}$) was significantly greater than at 60% 1RM. It is suggested, therefore, when performing midhigh clean pulls and the goal is to train RFD, it may be advantageous to train at a load of 120% 1RM to achieve peak values.

Finally, total impulse and impulse at 100, 200, and 300 milliseconds was each maximized at 140% 1RM, which should be expected as this is the load where the greater GRFs and RFDs are achieved. This supports the notion that to maximize force and measures of explosive force production, such as RFD and impulse, during midhigh clean pulls then higher loads should be incorporated.

It is suggested that future research should incorporate differential loading (40% 1RM for peak power; 120–140% 1RM for peak F_{max} , impulse, and RFD) during training studies to determine the effects of different loads on adaptive responses in terms of both the kinetics during the midhigh clean pull and sprint and jump performance. It is also worth noting that it has been suggested that peak power output in complex exercises may vary dependent on both relative strength and technical proficiency (2,31); therefore, further research clarifying the affect of such variables is suggested.

PRACTICAL APPLICATIONS

When designing training programs, it is essential to clearly identify which muscle strength quality is the primary focus, which subsequently determines the selection of an appropriate load and intensity. The results of this study indicate that peak power and velocity of movement during the midhigh clean pull is achieved at a load of 40% 1RM power clean. When training to maximize peak power output, lower loads are recommended in team sport athletes. Moreover if the goal is to train F_{max} , impulse or RFD higher loads, of 120–140% 1RM, are recommended. Finally, it is suggested that when developing training programs to improve power output such exercises should be periodized to progress from max strength (F_{max}) to peak power, in a sequential manner; therefore, it may be beneficial to begin at high loads (>100% 1RM) and progressively decrease loading to maximize velocity and power.

REFERENCES

1. Baechle, TR, Earle, RW, and Wathen, D. *Resistance Training*. In: *Essentials of Strength Training and Conditioning*. T. R. Baechle and R. W. Earle, eds. Champaign, IL: Human Kinetics, 2008. pp. 381–412.
2. Baker, D, Nance, S, and Moore, M. The load that maximizes the average mechanical power output during jump squats in power-trained athletes. *J Strength Cond Res* 15: 92–97, 2001.
3. Bevan, HR, Bunce, PJ, Owen, NJ, Bennett, MA, Cook, CJ, Cunningham, DJ, Newton, RU, and Kilduff, LP. Optimal loading for the development of peak power output in professional rugby players. *J Strength Cond Res* 24: 43–47, 2010.
4. Comfort, P, Allen, M, and Graham-Smith, P. Comparisons of peak ground reaction force and rate of force development during variations of the power clean. *J Strength Cond Res* 25: 1235–1239, 2011.
5. Cormie, P, Deane, R, and McBride, JM. Methodological concerns for determining power output in the jump squat. *J Strength Cond Res* 21: 424–430, 2007.
6. Cormie, P, McBride, JM, and McCaulley, GO. Validation of power measurement techniques in dynamic lower body resistance exercises. *J Appl Biomech* 23: 103–118, 2007.
7. Cormie, P, McBride, JM, and McCaulley, GO. Power-time, force-time, and velocity-time curve analysis during the jump squat: Impact of load. *J Appl Biomech* 24: 112–120, 2008.
8. Cormie, P, McGuigan, MR, and Newton, RU. Developing maximal neuromuscular power: Part 2-training considerations for improving maximal power production. *Sports Med* 41: 125–146, 2011.
9. Cortina, JM. What is coefficient alpha? An examination of theory and applications. *J Appl Psychol* 38: 98–104, 1993.
10. Enoka, RM. The pull in Olympic weightlifting. *Med Sci Sports* 11: 131–137, 1979.
11. Garhammer, J. Performance evaluation of Olympic weightlifters. *Med Sci Sports* 11: 284–287, 1979.
12. Garhammer, J. Power production by Olympic weightlifters. *Med Sci Sports Exerc* 12: 54–60, 1980.
13. Garhammer, J. Energy flow during Olympic weight lifting. *Med Sci Sports Exerc* 14: 353–360, 1982.
14. Garhammer, J. A Review of power output studies of Olympic and powerlifting: Methodology, performance prediction, and evaluation tests. *J Strength Cond Res* 7: 76–89, 1993.
15. Haff, GG, Kirksey, KB, Stone, MH, and Waren, BJ. The effect of 6 weeks of creatine monohydrate supplementation on dynamic rate of force development. *J Strength Cond Res* 14: 225–231, 2000.
16. Häkkinen, K, Kauhanen, H, and Komi, PV. Biomechanical changes in the Olympic weightlifting technique of the snatch and the clean & jerk from submaximal to maximal loads. *Scand J Sports Sci* 6: 57–66, 1984.
17. Harris, NK, Cronin, JB, and Hopkins, WG. Power outputs of a machine squat-jump across a spectrum of loads. *J Strength Cond Res* 21: 1260–1264, 2007.
18. Hori, N, Newton, RU, Andrews, WA, Kawamori, N, McGuigan, MR, and Nosaka, K. Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. *J Strength Cond Res* 21: 314–320, 2007.
19. Hori, N, Newton, RU, Andrews, WA, Kawamori, N, McGuigan, MR, and Nosaka, K. Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *J Strength Cond Res* 22: 412–418, 2008.
20. Kaneko, M, Fuchimoto, T, Toji, H, and Suei, K. Training effect of different loads on the fore-velocity relationship and mechanical power output in human muscle. *Scand J Sports Sci* 5: 50–55, 1983.
21. Kawamori, N, Crum, AJ, Blumert, PA, Kulik, JR, Childers, JT, Wood, JA, Stone, MH, and Haff, GG. Influence of different relative intensities on power output during the hang power clean: Identification of the optimal load. *J Strength Cond Res* 19: 698–708, 2005.
22. Kawamori, N, Rossi, SJ, Justice, BD, Haff, EE, Pistilli, EE, O'Bryen, HS, Stone, MH, and Haff, GG. Peak force and rate of force development during isometric and dynamic mid-high clean pulls performed at various intensities. *J Strength Cond Res* 20: 483–491, 2006.
23. Kilduff, LP, Bevan, H, Owen, N, Kingsley, MI, Bunce, P, Bennett, M, and Cunningham, D. Optimal loading for peak power output during the hang power clean in professional rugby players. *Int J Sports Physiol Perform* 2: 260–269, 2007.

24. McBride, JM, Triplett-McBride, T, Davie, A, and Newton, RU. The effect of heavy- vs light-load jump squats on the development of strength, power, and speed. *J Strength Cond Res* 16: 75–82, 2002.
25. Moss, BM, Refsnes, PE, Abildgaard, A, Nicolaysen, K, and Jensen, J. Effects of maximal effort strength training with different loads on dynamic strength, cross-sectional area, load-power and load-velocity relationships. *Eur J Appl Physiol* 75: 193–199, 1997.
26. Souza, AL and Shimada, SD. Biomechanical analysis of the knee during the power clean. *J Strength Cond Res* 16: 290–297, 2002.
27. Souza, AL, Shimada, SD, and Koontz, A. Ground reaction forces during the power clean. *J Strength Cond Res* 16: 423–427, 2002.
28. Stone, M. Explosive exercise and training. *Natl Strength Cond Assoc J* 15: 7–15, 1993.
29. Stone, MH, O'Bryant, HS, McCoy, L, Coglianese, R, Lehmkuhl, M, and Schilling, B. Power and maximum strength relationships during performance of dynamic and static weighted jumps. *J Strength Cond Res* 17: 140–147, 2003.
30. Stone, MH, Stone, M, and Sands, WH. *Principles and Practice of Resistance Training*. Champaign, IL: Human Kinetics, 2007.
31. Thomas, GA, Kraemer, WJ, Spiering, BA, Volek, JS, Anderson, JM, and Maresh, CM. Maximal power at different percentages of one repetition maximum: Influence of resistance and gender. *J Strength Cond Res* 21: 336–342, 2007.
32. Weyand, PG, Lin, JE, and Bundle, MW. Sprint performance-duration relationships are set by the fractional duration of external force application. *Am J Physiol Regul Integr Comp Physiol* 290: R758–R765, 2006.
33. Weyand, PG, Sandell, RF, Prime, DNL, and Bundle, MW. The biological limits to running speed are imposed from the ground up. *J Appl Physiol* 108: 950–961, 2010.
34. Weyand, PG, Sternlight, DB, Bellizzi, MJ, and Wright, S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 89: 1991–1999, 2000.
35. Wilson, GJ, Newton, RU, Murphy, AJ, and Humphries, BJ. The optimal training load for the development of dynamic athletic performance. *Med Sci Sports Exerc* 25: 1279–1286, 1993.